Producing Digital Elevation Models with Radar Interferometry

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Abstract. The main objective of this paper is to discuss how satellite radar interferometry (InSAR) can be applied for production of high-resolution digital elevation models (DEMs). DEM is the most important natural environment data layer used in the archaeological landscape analyses. From the high-resolution elevation models numerous essential information layers used in archaeological regional analyses can be derived: slope, aspect, cross sections, and inter-visibility. This data can be further on used for modeling of boundaries and territories as well as for optimal paths calculations. In the areas where suitable DEMs do not exist or are not available, interferometry is an effective alternative for their production. In this paper general background and the production of digital elevation model for Slovenia is presented. The results have proved that interferometry can be used for fast, effective and cheap production of accurate DEMs over large areas.
Keywords: radar interferometry, digital elevation model, image processing.

1 Introduction

Even just a short overview of the numerous applications of geographical information systems in archaeology can demonstrate that digital elevation model (DEM) is the most often used environmental data layer in current archaeological regional analyses. This comes as no surprise. Elevations and derivatives of the DEM are considered the most important limiting factors in the human use of land (Kvamme 1992). For example, present and past human settlements are limited by the elevation. Elevation directly influences air temperature and all other climatic variables that reduce the possibility of permanent settlements above a certain elevation. Higher slopes and north-facing orientation can also be understood as less favoured for human settlements (Kvamme 1988). From DEMs we can generate economic boundaries and territories of past societies and optimal paths between individual locations (Gaffney and Stančič 1991). With viewsheds in all different combinations with other variables we can model perception of space of archaeological societies (Wheatley 1995).

For most of these products, an accurate elevation model is essential. DEMs are usually either provided by government agencies or, when they are not available or of not adequate quality, will have to be generated (Robinson and Zubrow 1999; Belcher *et al.* 1999). There are essentially two basic principles of DEM production. The first one is from existing data and the second one is from new measurements. The first case is used when adequate topographic maps are available. It starts with digitalization of contour lines from maps, which after control, interpolation and filtering can provide satisfactory results (Podobnikar *et al.* 2000). In other cases DEM will have to be generated using new measurements. Classical geodetic techniques are used only if a high resolution DEM over a small area is required. In the past DEMs were produced mostly from stereoscopic air photographs. Since the mid 1980s, SPOT satellite is producing good quality and high-resolution stereoscopic images from space, which can be used both to generate DEMs and topographic maps on a scale of up to 1:50,000. After the launch of ERS-1 (European Remote Sensing Satellite 1) in the beginning of the 1990s, satellite radar interferometry (InSAR) is being considered as a possible source of data for DEM production.

At the Scientific Research Centre of the Slovenian Academy of Sciences and Arts we started a project to improve the existing Slovenian DEM 100. This was made by the Slovenian government authorities in the late 1970s and was successfully used in many applications. It is distributed as a raster database with cell sizes of 100 by 100 m and an estimated mean error of 10 m. DEM 100 could be used for general purposes; however its accuracy proved not to be sufficient, especially in flat areas (Podobnikar *et al.* 2000). For the purpose of accurate archaeological predictive modeling at least a DEM with a cell size of 25 by 25 m and a height accuracy of less then 5 m is needed. Since we wanted to use the most cost effective method we decided to produce the new DEM using radar images.

In this paper we will demonstrate how DEM can be produced using such radar interferometry. After this introduction, a general procedure for interferometric DEM production is presented. The results of practical application are presented and evaluated in section 3.

2 DEM generation

Radar interferometry is an advanced technique, which can be used to obtain high resolution Earth surface data from satellite or airborne radar images. Its most promising application fields are production of digital elevation models and observation of surface movements, especially in areas not well covered with "classical" methods. In digital elevation model production accuracy of approximately ten meters in horizontal and a few meters in vertical direction can be obtained.

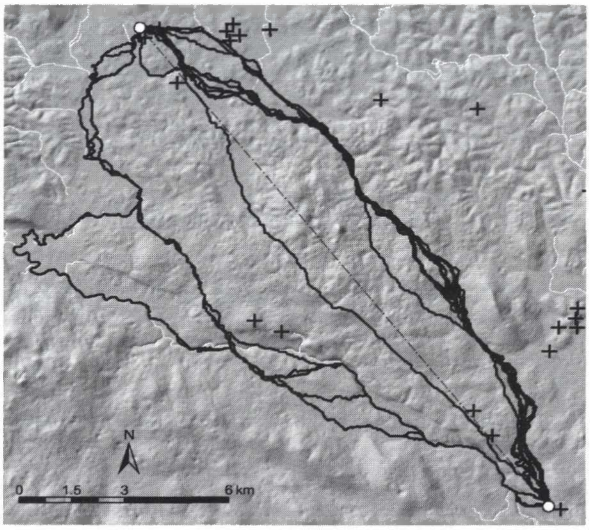


Fig. 1. Least cost pathways between two Bronze Age archaeological sites (white points) in southern Slovenia. Routes were modeled with different algorithms from the digital elevation model with a resolution of 25 by 25 m. The actual paths seem to be those that are shortest and at the same time near to barrows (black crosses)

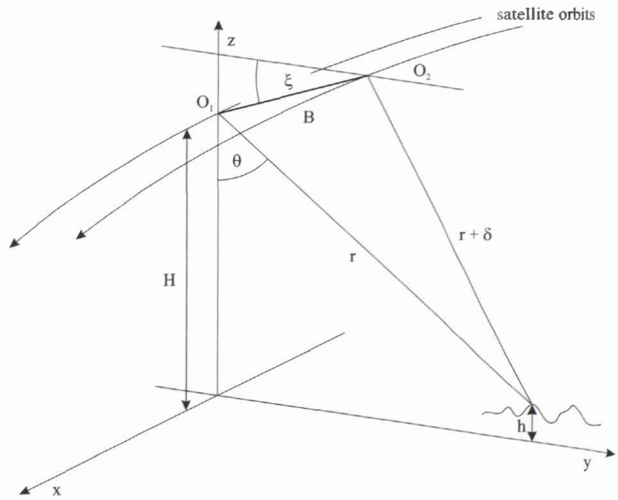


Fig. 2. Geometry of interferometric image acquisition

Differential interferometry enables detection of surface movements in the scale of fraction of used wavelength that is approximately half a centimeter for ERS satellites.

In interferometric processing pairs of complex radar satellite or airborne images are used. These contain both amplitude and phase of reflected microwaves. The complex phase depends both on the surface electromagnetic properties and the distance from the emitting antenna to target and back to receiving antenna (Fig. 2). When we have two images of the same area that were made from slightly different orbits, we can relate the interferogram – phase difference of the two images – to elevation on the ground

$$h \cong h_a \frac{\phi}{2\pi}. \qquad (1)$$

In (1) h_a is the ambiguity height, that depends on satellite parameters, such as height, wavelength and orbit separation. To obtain good results the viewing geometry and interferometric conditions will have to be considered with special care. Images have to be made from almost identical orbits and phase reflectance between image acquisitions must not change considerably. The latter is not easy to fulfil over longer periods, since surface variations – as vegetation growth – alter the phase properties considerably.

Theoretical background of interferometry has been known for more than twenty years and it has been more than fifteen years since the first successful interferometric processing. The breakthrough of interferometry occurred after 1991 when the first European remote sensing satellite ERS-1 was launched. Since then the technique has been used in numerous studies, ranging from hydrology and volcanology to seismology, glaciology, ecology and archaeology. Nonetheless, interferometry is still not operational. There are several reasons for this, most notably lack of standardized processing procedures, but also complicated software and problematic interferogram combination.

Production of the interferometric DEM over larger areas can be divided into several steps (Gens and Van Genderen 1996; Gens 1998; Oštir 2000, see Fig. 3):

1. Selection of image pairs
2. Interferometric processing
   a. precise image co-registration
   b. interferogram generation
   c. interferogram enhancement
   d. phase unwrapping
   e. phase to height conversion
3. Geocoding and height correction
4. Mosaicking.

2.1 Image selection

Image selection is the most critical step in the interferometric chain. Suitable images can speed up the processing, enhance the quality of the results or even prevent the DEM generation. To obtain the best results, detailed meteorological data, including the temperatures and amount of precipitation, has to be considered. If possible one should select tandem image pairs – ERS-1 and 2 acquired a large set of images one after another with one day separation. The processing can be successful with 'optimal' weather conditions (no rain or snow during and before image acquisition) and baselines (separation between image pairs) mainly in the range of 100 to 300 m (Gens 1998; Oštir 2000).

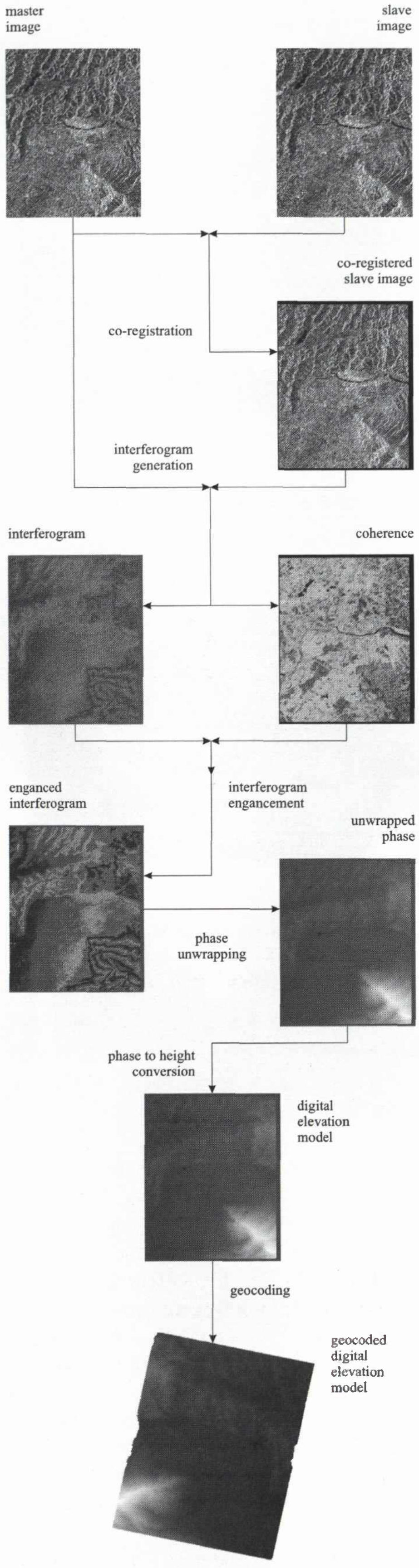


Fig. 3. Interferometric processing chain

The whole area of Slovenia can be covered with eight ERS scenes, either ascending or descending (Fig. 4). The elevation model of the country was entirely produced from tandem pairs. A combination of a total of twelve pairs – both from ascending (south to north, four) and descending (north to south, eight) satellite orbit was used. Coherence – that is the correlation between the image pair – is a significant measure of the interferogram quality (Rufino *et al.* 1997; Gens 1998). Relatively high coherence was achieved for all pairs, especially in areas not covered with lush vegetation. The coherence was lower in forested areas, where difficulties in processing could not be avoided. Most suitable images were found in months with non-active vegetation – early spring and late autumn. Very high coherence was achieved using images acquired when the soil was frozen.

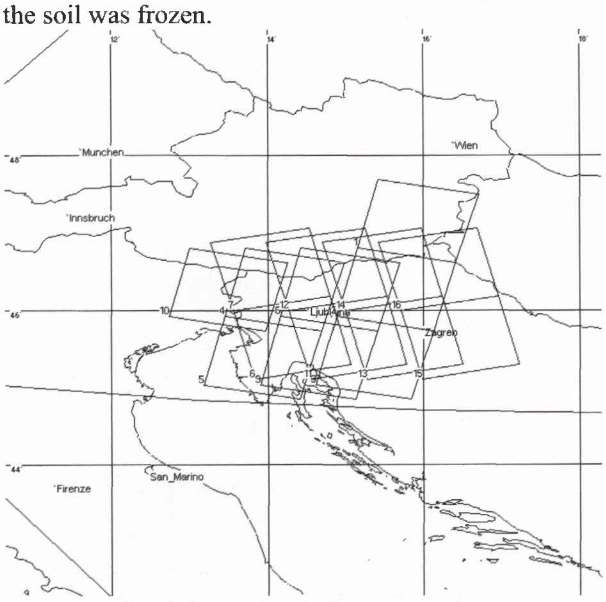


Fig. 4. The area of Slovenia can be covered with eight either ascending or descending SAR scenes. To eliminate the effects of layover and shadows, a combination of four ascending and eight descending images was used

2.2 Interferometric processing

Interferometric processing – including co-registration, interferogram generation and enhancement, phase unwrapping and conversion to height – was performed with the commercially available software package EarthView InSAR (Atlantis 1997). There are some other free and commercial InSAR programs, but in our experience not one is as capable and user friendly as EarthView.

The satellite scenes were divided into subscenes (at least four per image, each one approximately 50 by 50 km) to make the image size manageable for the hardware available. The rough DEM 100 was used for improvement of the quality and simplification of processing. Special care was paid to co-registration and phase unwrapping (elimination of phase ambiguity of 2π). Co-registration was done automatically and manually to improve coherence. Several algorithms were tested for image unwrapping and later iterative disk masking (Atlantis 1997) was selected, since it produced the best results and performed well even in areas with lower coherence.

2.3 Geocoding and height correction

The interferometric part of processing was performed in (slant) radar geometry and only in the final step the results were transformed into geographic coordinates with WGS 84 as reference. To use the height image as a DEM it is necessary to perform precise geocoding, horizontal positioning, and height correction, vertical positioning (Small 1998, Gens 1998, Schwaebisch 1995).

Each partial elevation model was corrected by applying a first order polynomial transformation in height. A general afine transformation was used to correct the plane coordinates. All reference data was taken from topographic maps on a scale of 1:25,000 (200 map sheets were used in total). Approximately 100 height and position control points per SAR scene were used, about one half for geocoding and the other for height correction. Since Slovenia uses the Gauss-Krueger coordinate system an additional transformation had to be applied at the end.

2.4 Mosaicking

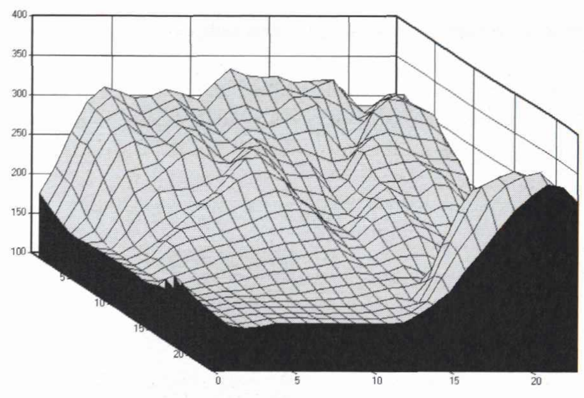
Ascending-descending orbit combination for DEM generation is a useful technique which can be applied to fill in the gaps in the DEM caused by the geometric deformations present on SAR images. The benefits of the combination over layover and foreshortening areas are evident thanks to the new data made available by the opposite pair. However, other areas in the image also improve in quality because of the averaging between the ascending and the descending pass (Carrasco *et al.* 1997).

The final DEM was produced as a combination of all available 'partial' models. A weighted average was used to combine the DEMs (Oštir 2000)

$$DEM_f(x,y) = \frac{\sum_i w_i(x,y) DEM_i(x,y)}{\sum_i w_i(x,y)} . \qquad (2)$$

In (2) DEM_i stands for models obtained from different image pairs or in different runs. The DEMs are weighted (w_i) with coherence – i.e. the model with higher coherence has a stronger influence on the final result. As already mentioned coherence is a natural measure of interferogram clearness and is therefore a logical choice for weights. The rough DEM 100 used in the interferometric processing was also included in the sum. For the height calculation of each point in the grid the average of two to four height values was used.

a)



b)

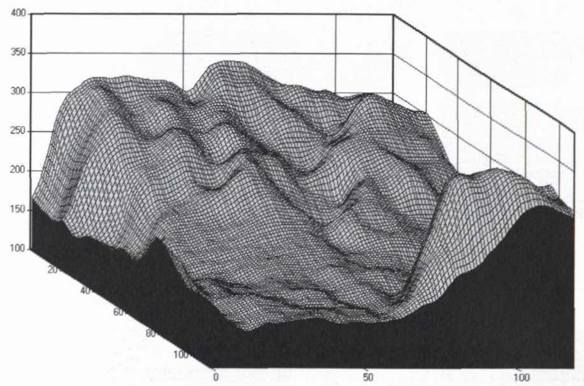


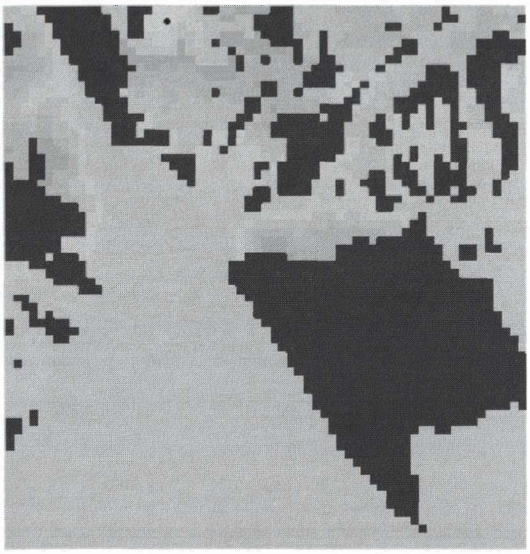
Fig. 5. Visual comparison of governmental DEM 100 (a) and interferometric InSAR DEM 25 (b). The later can be used much more effectively in applications such as archaeological modeling

3 DEM validation

In the last few years there has been an increased concern regarding the accuracy of spatial data. It is more and more important that every DEM is evaluated with various techniques. In our study visual and statistical validation was employed. For the reference, topographic maps on a scale of 1:25,000 were used. An accurate model was produced from contour lines, terrain characteristic points and other available height points (Podobnikar *et al.* 2000). For comparison also the model made from aerial ortophoto, which is being produced for the whole of Slovenia, was included. The test areas were selected according to relief variability (hilly areas, flat areas) and land-cover (urban area, forest, field, pasture).

Visual interpretation included comparison of contour lines, ridges, peaks and drainages, profiles, shadowed DEMs and perspective views (Figs. 5 and 6). While visual interpretation is a quick method for error detection, more reliable results are obtained with statistical methods.

a)



b)

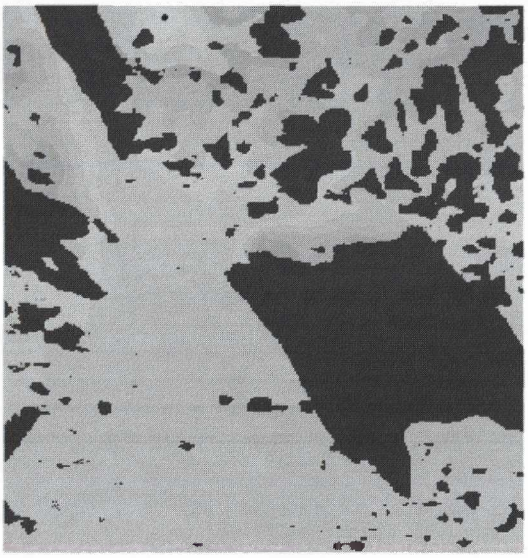


Fig. 6. Elevation model enhancement is even more obvious if analysis (e.g. visibility) is performed; DEM 100 (a) and InSAR DEM 25 (b)

With the combination of partial DEMs the vertical accuracy (RMSE) of InSAR DEM 25 between less than 2 and 10 m, depending on local relief variations, was obtained (Table 1). As can be seen in the table, interferometric – and ortophoto as well – DEM is slightly higher than the reference (approximately 1.5 m). The main cause for this is probably the influence of vegetation. The pixel size in the final model is 25 m, sufficient for modeling of larger areas.

Table 1. Accuracy of the final digital elevation model InSAR DEM 25 (aerial ortophoto DEM values are given for comparison)

Value	Interferometry	Orto-photo
Minimum difference	44 m	13 m
Maximum difference	-47 m	-36 m
Average difference	1.5 m	1.0 m
RMSE in flat areas	1.8 m	2.3 m
RMSE in hilly areas	9.8 m	4.7 m
RMSE together	3.1 m	3.0 m

4 Conclusions

Digital elevation model is the most often used environmental data layer in numerous applications of geographical information systems, including archaeological regional analyses. Therefore it is usually the first data layer obtained when a GIS system is established. In the areas where suitable DEM does not exist, one has to generate it from available data. There are several methods for DEM production, varying in speed, accuracy and cost. One of the best alternatives to 'classical' modeling (interpolation) is interferometric processing.

In our experience radar interferometry can be successfully used to produce DEMs of larger areas. Interferometry is slowly becoming an operational technique, but still needs careful processing and highly dedicated software. Special care has to be taken in selection of the input images. The results are best when ascending-descending pairs are used and images are taken in a period of non-active vegetation, especially when the soil is frozen. Another important factor is georeferencing, which has to be done with many ground control points (for position and height). Mosaicking of partial DEMs has to be done with an advanced method, such as coherence weighted averaging. The interferometric elevation models have an overall accuracy that is comparable with other production methods. In our case study the InSAR DEM 25, produced for the whole of Slovenia, has an overall RMSE of approximately 3 m. This result is relatively good and could not be obtained without advanced interferogram combination and the use of external (coarse) DEM 100.

While interferometric DEMs can be used in various studies we see their potential also as one of the sources in advanced DEM production. They can be coupled with all available elevation data, as vector contour lines from maps, hydrographic elements, break lines, relief characteristic points, geodetic points, photogrammetricaly captured elevations, etc. If adequate processing is used all this data can lead to an advanced and up-to-date DEM.

Acknowledgments

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